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Dynamical evidence for black holes and dark halos

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Abstract: A variety of observational approaches have provided evidence for extended halos of dark matter surrounding elliptical galaxies, and for massive dark objects in (some of) their nuclei. What are the properties of the dark halos? How do they relate to the parameters of the luminous matter? What is the demographics of massive central black holes, and what is their dynamical role in shaping the host galaxy? Recent work in this area is described, with special attention to the construction of state-of-the-art dynamical models that incorporate all available observational constraints.

1. Introduction

One of the fundamental questions of astronomy is: *How did galaxies form, and how do they evolve?* Elliptical galaxies are of particular interest in this area, since their stellar populations are among the oldest in the Universe. They display a rich variety of physical properties. The inner tens of parsecs often contain stellar and gaseous disks, possibly associated with massive central black holes, as well as unresolved nuclear spikes, kinematically decoupled structures, double nuclei, and puzzling asymmetries (e.g., Jaffe et al. 1994; Lauer et al. 1995, 1996; Carollo et al. 1997). The nuclear properties appear to correlate with the global structure of the parent galaxy. For example, the luminosity-density profiles of ellipticals approach a power-law form $\rho(r) \propto r^{-\gamma}$ at small radii r, where the giant ellipticals (with $M_B < -22.0$) have *shallow* cusps (mean $\gamma \sim 0.8$), while low-luminosity ellipticals (with $M_B > -20.5$) have *steep* cusps (mean $\gamma \sim 1.9$; Gebhardt et al. 1996). At intermediate luminosities both types of nuclear profile occur. It is unclear whether these properties were imposed by the galaxy formation process, or are the result of subsequent evolution (possibly influenced by the environment), or both: Does the formation of the nucleus determine the structure of the galaxy, or is it a repository of low angular momentum material collected over the life-time of the galaxy? What is the role of mergers, and of the physical processes they might trigger? Do they destroy pre-existing steep cusps to make larger systems with shallower cusps? Crucial issues are:

(i) What is the role of dark halos? Cosmological simulations suggest that dark matter halos have a mildly cusped universal density profile, and that they have a range of triaxial shapes. The luminous galaxy forms by infall of baryonic material. This results in a contraction of the dark halo, and a modification of its shape. What is the relation between the profile and

the shape of the contracted dark halos and the properties of the luminous galaxy in it?

(ii) What is the role of a central massive dark object? Do all ellipticals contain one? Is this a black hole? What is the distribution of black hole masses? How does the black hole mass relate to the global/nuclear properties of the parent galaxy? What is the dynamical relevance of the black hole? Does it drive the galaxy towards axisymmetry from the inside out?

Observational and theoretical efforts are needed to answer these fundamental questions. Two-dimensional spectroscopy over the entire optical extent of the galaxies is required, complemented by high spatial resolution imaging and spectroscopy of the nuclei. In addition, the construction of flattened multi-component dynamical models that have the full variety of anisotropic velocity distributions is essential for a correct interpretation of this data.

2. Determination of unseen mass

Studies of the dark matter content of elliptical galaxies concentrate on the properties of (i) dark halos surrounding the luminous galaxies, and (ii) massive dark objects such as black holes in their nuclei. In both cases we need to measure the *total* mass-to-light ratio M/L as a function of position, and then to compare it with the *stellar* M/L of the luminous matter. This requires several steps.

2.1 Intrinsic shapes

The luminosity distribution L is usually found by deprojecting the surface brightness distribution. This deprojection is non-unique, and requires the determination of the intrinsic shape for the galaxy, and of the direction of viewing. The mass distribution M is derived from the total gravitational potential. In some cases this can be inferred from the emission of extended X-ray gas (e.g., Forman, Jones & Tucker 1985; Buote & Canizares 1996), from gravitational lensing (Maoz & Rix 1993; Kochanek 1995), or from the kinematics of cold gas at large (Franx et al. 1994) or small (Harms et al. 1994) radii. In general, however, the potential must be derived by dynamical modeling of the stellar kinematics, either obtained from integrated light measurements, or from radial velocities of individual objects such as planetary nebulae and globular clusters. This again requires the determination of the intrinsic shape and of the viewing direction.

2.2 Orbital structure

Giant elliptical galaxies very likely have stationary, or at most slowly tumbling, triaxial figures. The orbital structure of (even mildly) triaxial systems is rich, and depends on the tumbling rate, the degree of triaxiality, and the central mass concentration. Theoretical work carried out in the past two decades has established that dynamical models with shallow cusps can be constructed for a wide range of triaxial shapes (see the review by de Zeeuw 1996, and references therein). The stars in such models may occupy box orbits, various families of tube orbits, minor orbit families, or irregular orbits. There are many ways to populate the different orbits so as to reproduce the same triaxial shape. The

resulting dynamical models therefore differ in their velocity distributions. The regular box orbits disappear in models with steep cusps, and the minor orbit families as well as the irregular orbits become more important (Gerhard & Binney 1985; Miralda-Escudé & Schwarzschild 1989). This change in orbital structure may limit the degree of triaxiality of equilibrium models for low-luminosity ellipticals: few or no orbit combinations can reproduce a steep-cusped strongly triaxial model (Kuijken 1993; Schwarzschild 1993; Merritt & Fridman 1996). Similarly, it is suspected that strongly triaxial models with massive central black holes can not be in dynamical equilibrium. However, much is still to be learned about the allowed degree of non-axisymmetry.

2.3 Measuring the velocity anisotropy

The anisotropy of the velocity field must be measured in order to distinguish its variations from true M/L variations caused by unseen matter (e.g., Binney & Mamon 1982; Gerhard 1993). Recently, techniques have been developed to measure not only the mean streaming velocities $\langle v \rangle$ and velocity dispersions σ, but also the shape of the entire line-of-sight velocity distribution (velocity profile VP; e.g., Rix & White 1992; van der Marel & Franx 1993). The VP shapes constrain the anisotropy of the velocity distribution. These measurements require high signal-to-noise high spectral resolution spectroscopic data, which can now be obtained routinely (e.g., van der Marel et al. 1994; Carollo et al. 1995; Statler et al. 1996).

2.4 Dynamical modeling

Finally, fully general dynamical models are required to derive the mass distribution from the measured VPs. These models must: (i) not require the availability of analytic integrals of motion; (ii) put no restrictions on the form of the gravitational potential, and thus allow for arbitrary geometry and the inclusion of a central black hole; (iii) allow for multiple luminous components such as nuclear disks and kinematically decoupled structures; (iv) put no restriction on the form of the velocity distribution, and thus allow exploration of the full range of velocity anisotropy. Advances in computer technology make it now possible to construct such models, as discussed below.

3. An extension of Schwarzschild's Method

A versatile method for building galaxies was introduced by Schwarzschild (1979, 1982), who used it to establish the existence of triaxial equilibrium models for galaxies with finite density cores, stationary as well as tumbling. In the original version of the method, stellar orbits were integrated numerically in a chosen galaxy potential, and then populated so as to reproduce the associated density distribution. Richstone (1980, 1984) built scale–free axisymmetric models with this technique. In the past decade the method has been used to build a variety of spherical, axisymmetric and triaxial galaxy models which also include the observed velocity dispersions as constraints (e.g., Richstone & Tremaine 1984, 1985; Pfenniger 1984; Levison & Richstone 1985; Zhao 1996).

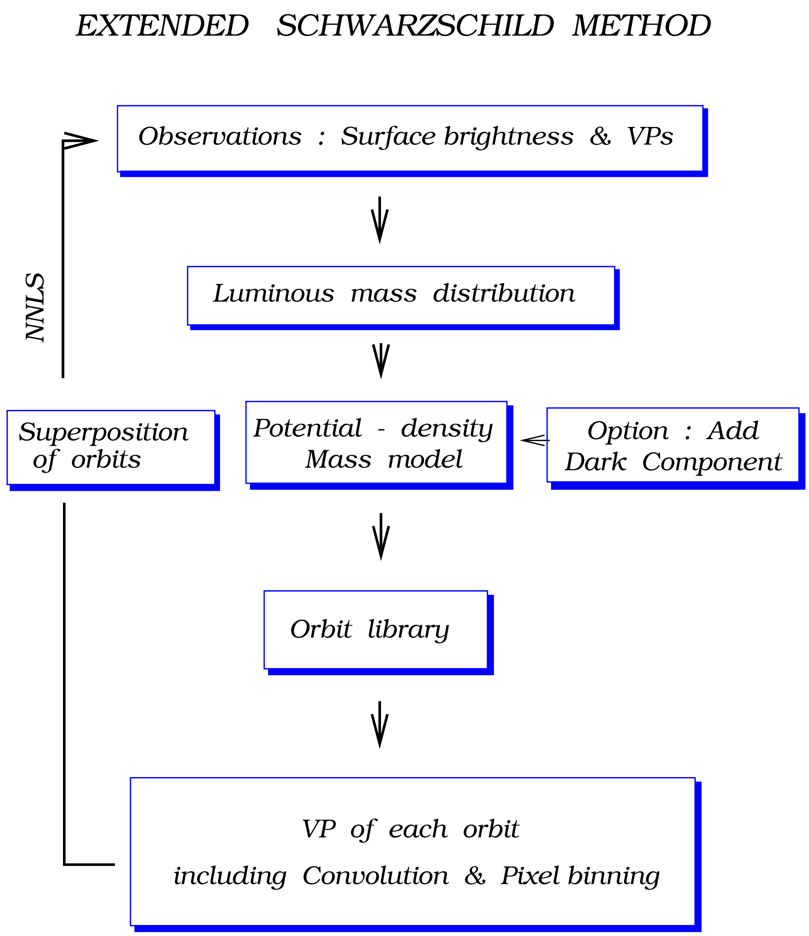

Figure 1. Flowchart of the extended version of Schwarzschild's numerical orbit superposition method for the construction of fully general dynamical models for galaxies. The velocity profiles (VPs) of each orbit are fitted to the observed surface brightness and kinematic measurements by means of a non-negative least squares (NNLS) algorithm.

We have recently extended the Schwarzschild method further by incorporating the entire VPs as constraints in the construction of fully anisotropic models with arbitrary geometry. We are therefore finally in the position to quantify the velocity distribution in ellipticals, and to measure their dark matter content. We have completed the spherical version of the code (Rix et al. 1997), as well as the axisymmetric version (Cretton et al. 1997; van der Marel et al. 1997c). A similar code for tumbling geometry, and for lopsided systems, is under construction (Zhao et al. in preparation). A further extension will include velocity measurements of individual objects (e.g., planetary nebulae or globular clusters).

Our version of Schwarzschild's method consists of the following steps, illustrated in Figure 1: (i) a mass density is chosen that fits the galaxy photometry after projection; (ii) the gravitational potential is calculated, including the

contribution of dark components such as a nuclear point mass or an extended halo; (iii) a representative sample of orbits is calculated; (iv) the contribution of each orbit to the observed surface brightness and the observed VPs is calculated. These orbital VP contributions are convolved with the appropriate Point Spread Function, and aperture binned; (v) a non-negative least-squares (NNLS) fit is performed to determine the combination of orbits that reproduces the photometric and kinematic observations, taking into account the observational errors. A smoothness criterion is used to exclude solutions with very uneven populations of neighboring orbits.

Examples of orbital VPs can be found in Cretton's contribution to this volume. Our implementation uses the Gauss-Hermite expansion of the VPs of the orbits and of the model, i.e., we calculate the orbital contributions to the mean rotation velocity $\langle v \rangle$, to the velocity dispersion σ, and to the parameters h_i (with $i = 3, 4, \ldots$) which quantify the non-Gaussian shape of the VP (van der Marel & Franx 1993). Other ways of parametrizing the VPs can be used as well, including straight binning in the velocity coordinate, as long as this yields linear constraints. The Gauss-Hermite expansion uses a modest number of parameters, and hence does not require excessive cpu time and storage space.

The applications of this machinery are many. Below we briefly illustrate its power in constraining the mass distribution in ellipticals by considering the case of the massive black hole in the nucleus of M32, and the case of the dark halo around the E0 galaxy NGC 2434. More extensive descriptions of these applications can be found in the contributions to this volume by van der Marel and by Rix, respectively.

4. The black hole in M32

The search for central massive dark objects in the nuclei of quiescent elliptical galaxies has received much attention in the past two decades, with a steady improvement in the quality of the data, and in the sophistication of the modeling techniques (Kormendy & Richstone 1995). In order to find stellar dynamical evidence for a massive central dark object, we need to probe inside the radius where the stellar motions are dominated by the gravitational field of the dark object. This radius of influence is typically of the order of $1''$ or less, so spectroscopic observations at HST angular resolution (e.g., Kormendy et al. 1996; Richstone, van den Bosch, van der Marel, all elsewhere in this volume), or better, are required.

M32 is a low-luminosity E3 galaxy with a steep stellar cusp. The inner region shows no minor axis rotation and no isophote twist. This is circumstantial evidence that M32 is likely to be nearly axisymmetric. It has been suspected of harboring a black hole for over a decade, but so far all mass determinations were based on a comparison of ground-based data with either spherical models with general velocity distributions, or with flattened models with special distribution functions (Tonry 1987; Dressler & Richstone 1988; van der Marel et al. 1994; Qian et al. 1995; Bender, Kormendy & Dehnen 1996).

We have recently obtained `FOS` spectra at 8 positions along the major axis of M32, within the inner $0.5''$. We have applied the extended Schwarzschild method to build axisymmetric models that match the combined ground-based and `FOS` kinematics (van der Marel et al. 1997a, b, c). Our modeling follows the scheme of Figure 1, where the dark potential is taken to be either the Keplerian potential of a point mass (to describe a massive black hole), or that of a model with a finite scale-length, such as a Plummer potential or a cusped model (to describe a dense cluster of dark objects, see e.g., Gerhard 1994).

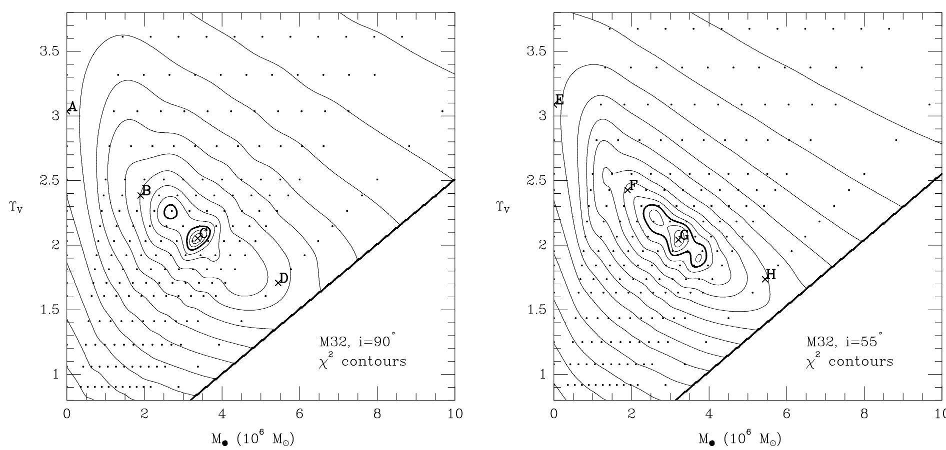

Figure 2. Contours of the χ^2 that measures the quality of fit to groundbased and `FOS` kinematic data for M32, for models with a fully general dynamical structure, in the plane of $M_{\rm BH}$ and stellar mass-to-light ratio Υ_V (in solar units). The dots indicate dynamical models that were calculated. The dynamical structure and predicted kinematics of the models labeled A-H are discussed in van der Marel et al (1997c). The first three (heavy) contours define the formal 68.3%, 95.4% and 99.73% confidence regions. a) edge-on model; b) inclined model. The case of no central dark mass is firmly ruled out: the mass of the central object lies in the range $(3.4 \pm 1.6) \times 10^6 M_\odot$.

The models have three free parameters: the V-band mass-to-light ratio Υ_V of the stellar population, the dark mass $M_{\rm BH}$, and the inclination i. However, we need to calculate only one orbit library for models with the same value of $M_{\rm BH}/\Upsilon_V$, since the potentials of such models are identical except for a normalization of the velocity scale. Each $(M_{\rm BH}, \Upsilon_V)$ combination does instead require a separate NNLS fit.

All models at a chosen inclination are constructed for the same parametrized luminous density distribution, which is fixed by fitting its projection to the surface brightness distribution of M32, determined from ground-based and HST data (Lauer et al. 1992). If M32 is axisymmetric, the deprojection of the surface brightness distribution is unique for $i = 90°$, but is non-unique for other inclinations (Rybicki 1987). So, our parametrization of the luminous density may not be the right model if $i \neq 90°$, even though it fits the projection. However, van den Bosch (1997) has used the formalism of konus densities introduced by Gerhard & Binney (1996) and Kochanek & Rybicki (1996), and concluded that non-uniqueness in the deprojection of M32 is negligible.

Because the measurement errors are taken into account in the NNLS fit to the data, we are able to compare the different dynamical models in an objective way, by computing the χ^2 of each fit. The result is illustrated in Figure 2. The left panel shows the $(M_{\rm BH}, \Upsilon_V)$ plane for the edge-on case $i = 90°$. The right hand panel shows the same diagram for $i = 55°$. In both panels there is a clear minimum in the χ^2 contours, for $M_{\rm BH} \sim 3.4 \times 10^6 M_\odot$. Representative orbits in the best fitting edge-on model are illustrated in Cretton's contribution to this volume. Based on extensive simulations of observational errors, and of discretization errors in the numerical procedure, the conservative estimate is that the allowed range for $M_{\rm BH}$ is $(3.4 \pm 1.6) \times 10^6 M_\odot$, independent of the inclination. The modeling also puts an upper limit on the dimensions of the dark mass, and rules out that the central object is an extended cluster of dark remnants. This finally puts the presence of a black hole in M32 beyond doubt!

5. The dark halo of NGC 2434

Even though the existence of dark matter around elliptical galaxies is established, it remains unclear whether the stellar and dark mass are as tightly coupled as they appear to be in spiral galaxies, where they conspire to give a flat rotation curve, and how the dark halo properties correlate with those of the luminous galaxy. Part of the difficulty comes from our ignorance about the form of the dark potential.

We have used our version of Schwarzschild's method to measure the dark matter content of the E0 galaxy NGC 2434. We have firmly ruled out constant M/L models for this galaxy, regardless of the orbital anisotropy. Furthermore, we have considered the cosmologically motivated 'star+halo' potentials of Navarro et al. (1996; see also Cole & Lacey 1996), modified so as to incorporate the accumulation of baryonic matter under the assumption of adiabatic invariance. These 'star+halo' potentials provide an excellent fit to the data. The best fitting potential has a circular velocity that is constant to within $\sim 10\%$ between 0.2 and 3 effective radii. Roughly half of the mass inside one effective radius is found to be dark.

We are currently extending this program to study the dark matter properties of a statistically significant number of ellipticals, covering a large range in luminosity.

6. The next steps

Major progress in this area is just around the corner. On the observational side, the kinematics of the bright nuclear regions are being studied at the appropriate resolution to measure the signature of massive central black holes, especially in quiescent galaxies. `STIS` on HST will improve the efficiency of these studies by providing long-slit spectra with $0.1''$ resolution. In addition, *two-dimensional* (integral field) spectroscopy is finally unveiling the rich structure of the velocity fields and line-strength distributions of triaxial and multi-component systems. For the investigation of the nuclei, integral field spectrographs with small fields

Table 1. Specifications of SAURON

Spatial sampling	$0.3''$	$1.0''$
Field of view	$10.3'' \times 9.0''$	$34.5'' \times 29.9''$
Spectral resolution	65 km/s	73 km/s
Spectral sampling	1.3 Å/pixel	1.3 Å/pixel
Spectral range	4820–5410 Å	4820–5410 Å

of view but high spatial resolution (0.1–$0.25''$, by use of adaptive optics) are currently being constructed at a number of major observatories, including `OASIS` at the Canada-France-Hawaii Telescope, and `GMOS` for Gemini. For studies of the dark halos, intermediate spatial resolution spectroscopy over the entire optical extent of elliptical galaxies is needed. To this end, the Observatoire de Lyon, the Astronomy group at the University of Durham, and the Leiden Observatory have recently formed the `SAURON` Consortium, with PI's Bacon, Davies & de Zeeuw, and co-I's Carollo, Emsellem, Monnet & Allington-Smith, to build the integral-field spectrograph `SAURON` (Spectroscopic Areal Unit for Research on Optical Nebulae), for use on a 4m class telescope such as the WHT on La Palma. `SAURON` uses an array of hexagonal lenslets that provides nearly 1500 simultaneous spectra at $1''$ resolution in a $30'' \times 35''$ field of view with a separate option for accurate sky-subtraction (120 spectra at $2.2'$ from the field center). The instrument also has a high spatial resolution mode (see Table 1). `SAURON` will allow us to measure the full, complex, kinematics and metallicity distributions of the giant elliptical galaxies. The extended Schwarzschild method will be used to model these data. The dynamical models will be constructed from orbits that not only cover phase-space, but also come in different flavors, i.e., different values of the line-strength. The extra constraints provided by the two-dimensional line-strength observations will then allow the determination of the intrinsic physical properties of the stellar populations as a function of position in the galaxy.

On the theoretical side, it is essential to investigate further the question of the existence of triaxial equilibria as a function of shape, cusp slope, tumbling rate, and presence of a central dark mass or a dark halo. Furthermore, the central stellar density in some ellipticals with a cusp is so high that the two-body relaxation time for stellar encounters becomes significantly less than a Hubble time, so that the collisionless approximation fails sufficiently close to the center. This has as yet received little attention in the context of galactic nuclei. An accurate treatment of secular evolution, such as driven by the growth of a central black hole, is the next frontier for N-body simulations. Issues to be addressed include the role of the central black hole in determining the cusp slope and shape of the host galaxy, and the effect of the capture of another galaxy, possibly with its own black hole.

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